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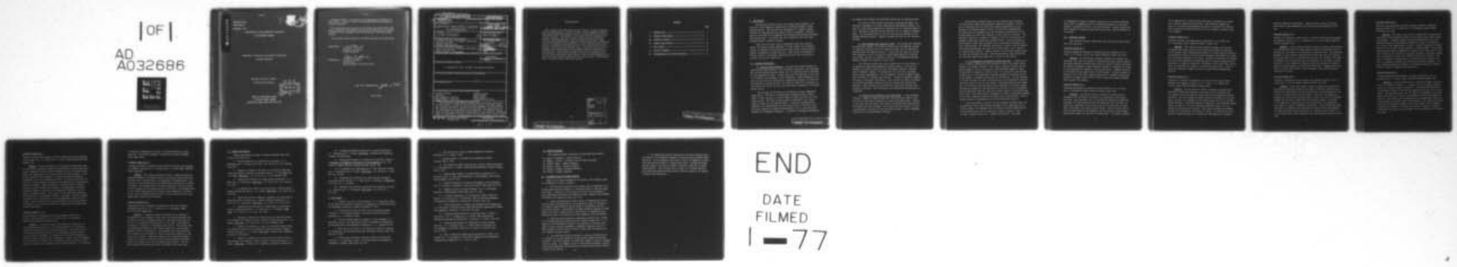

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Final Report
September 1976

APPLICATIONS OF MATRIX METHODS TO RADIATION AND SCATTERING SYSTEMS

Department of Electrical and Computer Engineering
Syracuse University

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ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

Professor Roger F. Harrington is the responsible investigator for this contract. Peter R. Franchi is the RADC/ETER Project Engineer (Contract Monitor).

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This technical report has been reviewed and approved for publication.

APPROVED: Peter R Franchi
PETER R. FRANCHI
Project Engineer

APPROVED: Allan C Schell
ALLAN C. SCHELL
Acting Chief
Electromagnetic Sciences Division

FOR THE COMMANDER: John P. Huss

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Electromagnetic scattering	Waveguide-fed apertures

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of this research project was to investigate applications of matrix methods to radiation and scattering systems. Four major topics were investigated, namely, (a) antenna pattern synthesis, (b) wire antennas over imperfect ground, (c) radiation and scattering from large bodies, and (d) electromagnetic transmission through apertures. All technical reports issued on project work are listed and abstracts of each are given. Published papers and oral papers related to project work are also listed. Based on the results of this project, recommendations for further research work are given.

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EVALUATION

This report is the Final Report on the contract. It covers research done on the application of matrix methods to electromagnetic radiation and scattering systems during the forty-two month period from January 1973 to June 1976. The objective of the research is the generation of analytic techniques and user oriented computer programs using the method of moments approach to four general problem areas. These areas are: (1) antenna pattern synthesis, (2) wire antennas over imperfect ground, (3) radiation and scattering from large bodies and (4) electromagnetic transmission through apertures. The practical result of this program is the availability of these computer programs and analytic techniques for a wide variety of important Air Force problems such as low frequency communication antennas located at very different sites (electrically), large radar target behavior, and complicated phased array apertures such as flush mounted multi-frequency arrays. This information is available in twelve scientific reports.

CONTENTS

I. INTRODUCTION

The objective of this project was to apply matrix methods to the solution of electromagnetic radiation and scattering problems of engineering interest. Each solution was implemented by a computer program suitable for computing data for general classes of problems. Each program was listed and fully documented with operating instructions and sample input-output data. It is hoped that other researchers will find these programs useful for similar problems.

There were four major topics investigated under this contract, namely, (A) Antenna pattern synthesis, (B) Wire antennas over imperfect ground, (C) Radiation and scattering from large bodies, and (D) Electromagnetic transmission through apertures. These topics are discussed in the next section. The reports resulting from this work, including abstracts, are listed in Section III.

II. PROBLEMS INVESTIGATED

A. Antenna Pattern Synthesis. Some general numerical methods for synthesizing antenna patterns, with and without constraints, were developed. Most pattern synthesis methods assume that the radiation field is specified in both magnitude and phase. In many cases only the magnitude of the field is of interest, and the phase is left unspecified. Cases considered in our work are (1) field pattern specified in amplitude and phase, (2) field pattern specified in amplitude only, (3) these two cases with a constraint on the source norm, and (4) the first two cases with a constraint on the source quality factor.

The solutions were obtained by the methods of finite dimensional linear spaces. The source is discretized by assuming either a finite number of point sources, or a finite number of basis functions for a continuous source. The field is discretized by evaluating it at a finite number of points on the radiation sphere. A matrix is obtained which represents the transformation from the source vector to the field vector. The matrix equaiton is normally overdetermined, that is, there are fewer unknowns than independent equations. A solution is obtained by minimizing the squared error between the synthesized pattern and the desired pattern.

For case (1), field pattern specified in amplitude and phase, the solution is obtained by the usual least-squares approximation method. For case (2), field pattern specified in amplitude only, an iterative method is used. The phase is adjusted in each iteration so as to reduce the squared error. For constrained cases (3) and (4) solutions are obtained via the Lagrange multiplier method. Computer programs are given for all solutions obtained.

B. Wire Antennas over Imperfect Ground. This problem was considered in three steps, namely, (1) parallel vertical wires over imperfect ground, (2) parallel horizontal wires over imperfect ground, and (3) arbitrarily oriented wires over imperfect ground. In each case two types of solution were considered, that of treating the ground approximately by reflection coefficients, and that of treating it exactly by the Sommerfeld integral. Computer programs are available for each case.

The solutions involve thin wires situated over the flat surface of an imperfectly conducting homogeneous isotropic ground. All wires are assumed to be perfect conductors with wire losses treated as a special case of impedance loading. The moment method is used with a piecewise linear current approximation. This corresponds to using triangular expansion functions in a Galerkin type solution. A number of numerical examples are given to illustrate the solution. Also, methods are given for optimizing certain performance indices of arrays of arbitrarily oriented wire antennas. These indices include directivity, power gain, and main beam radiation efficiency. Both constrained and unconstrained optimization are considered.

C. Radiation and Scattering from Large Bodies. It was originally desired to combine the moment method with the geometrical theory of diffraction to obtain matrix solutions for large conducting bodies. However, it was found that GTD alone, when multiple reflections were accounted for, was adequate for many problems. Our solution therefore reduced to a GTD solution where all orders of reflection were included. This is sometimes referred to as a self-consistent solution.

The particular problem carried out was radiation and scattering from electrically large convex polygonal conducting cylinders. Only the case of transverse electric fields was considered explicitly, but the extension to transverse magnetic fields is relatively straightforward. We started from the assumption that the diffraction coefficients for conducting wedges are known, and proceeded to apply them for a solution. The prototypic problem of a filament of magnetic current in the vicinity of a polygonal conducting cylinder was considered first. From that solution, the solutions to many other problems, such as plane-wave scattering, radiation from apertures, and radiation from electric currents, can be obtained. Illustrative computations are given for the above cases. For a check of the computational accuracy, a moment solution to the H-field integral equation was also developed and used. The program listing, with instructions for using and sample input-output data, is given in the reports.

D. Electromagnetic Transmission Through Apertures. A general solution to aperture problems has been obtained in terms of the moment method applied to an operator equation. This operator equation involves the tangential magnetic field in the aperture, with equivalent magnetic current (proportional to tangential electric field) in the aperture as the unknown. An application of the equivalence principle separates the problem into two parts, namely, the regions on each side of the aperture. The only coupling is through the aperture, whose characteristics can be expressed by aperture admittance matrices, one for each region. These admittance matrices depend only on the region being considered, being independent of the other region. The aperture coupling is then expressible as the sum of the two independent aperture admittance matrices, with source terms related to the incident magnetic field. This result can be interpreted in terms of generalized networks as two n-port networks connected in parallel with current sources. The resultant solution is equivalent to an n-term variational solution.

Since the problem is divided into two mutually exclusive parts, one can separately solve a few canonical problems, such as apertures in conducting screens, in waveguides, and in cavities, and then combine them in various permutations, such as waveguide to cavity coupling, cavity to cavity coupling, and so on. Specific solutions for the cases of transmission through a rectangular aperture in a perfectly conducting plane, and of transmission from a rectangular waveguide into half space through a rectangular aperture, have been developed. General purpose computer programs for these two cases have been written, and are available in the reports.

III. SCIENTIFIC REPORTS

The Scientific Reports issued under this contract are listed below with their abstracts:

Scientific Report No. 1

"Special Programs for Analysis of Radiation by Wire Antennas," by B. J. Strait, T. K. Sarkar, and D-C Kuo, Report AFCRL-TR-73-0399, June 1973.

ABSTRACT: Two user-oriented computer programs are presented and described. The first is suitable for handling efficiently typical analysis and design problems involving linear arrays of parallel thin-wire antennas. The second is designed to enable efficient analysis of radiation from vertical wire antennas over systems of radial ground wires. Examples are given to illustrate various applications of both programs. Special attention is devoted to use of the first program together with a standard optimization procedure to design linear arrays of wire elements with unequal spacings and/or unequal wire lengths.

Scientific Report No. 2

"Computational Methods for Antenna Pattern Synthesis," by J. R. Mautz and R. F. Harrington, Report AFCRL-TR-73-0500, August 1973.

ABSTRACT: Some general numerical methods for antenna pattern synthesis, with and without constraints, are developed in this report. Particular cases considered are (1) field pattern specified in amplitude and phase, (2) field pattern specified in amplitude only, (3) these two cases with a constraint on the source norm, and (4) the first two cases with a constraint on the source quality factor. Both the source and the field are discretized at the beginning, and the methods of finite dimensional vector spaces are used for the computations. The theory is general but is applied only to point sources arbitrarily distributed in a plane, and to pattern synthesis in this plane. Some numerical examples are given for ten sources approximately equispaced on one-half of an ellipse, with the desired field pattern chosen to be the cosecant ϕ pattern in the first quadrant.

Scientific Report No. 3

"Computer Programs for Antenna Pattern Synthesis" by J. R. Mautz and R. F. Harrington, Report AFCRL-TR-73-0654, October 1973.

ABSTRACT: This report contains computer programs, instructions, and sample input-output data for antenna pattern synthesis as developed in the previous report "Computational Methods for Antenna Pattern Synthesis." The programs are valid for point sources arbitrarily distributed in a plane, and for pattern synthesis in this plane. Included are programs for synthesis with (1) pattern magnitude and phase specified, (2) pattern magnitude only specified, (3) these two cases with a constraint on the source norm, and the first two cases with a constraint on the source quality factor. Also included are programs to compute and plot the specified and synthesized patterns.

Scientific Report No. 4

"Programs for Analysis of Radiation by Linear Arrays of Vertical Wire Antennas over Imperfect Ground," by B. J. Strait, T. K. Sarkar, and D-C Kuo, Report AFCRL-TR-74-0042, January 1974.

ABSTRACT: Two user-oriented computer programs are presented and described for analyzing radiation from linear arrays of vertical thin-wire antennas over the horizontal plane surface of an imperfectly conducting earth. The first program can handle arbitrary excitation of the array wires, although it is assumed they are equally spaced and all of the same length and radius. The second program is equipped to treat unequally spaced arrays of wires that can be of different lengths and radii, but it is assumed the wires are all centerfed. Both assume the wires are unloaded and that the conductivity of the earth is finite. The effects of the imperfectly conducting earth are accounted for approximately by using the method of reflection coefficients. Computed output consists of current distributions, input impedances, and far-field patterns specified by the user.

Scientific Report No. 5

"Analysis of Radiation by Linear Arrays of Parallel Horizontal Wire Antennas over Imperfect Ground," by T. K. Sarkar and B. J. Strait, Report AFCRL-TR-74-0538, September 1974.

ABSTRACT: A user oriented computer program is presented and described for analyzing radiation from linear arrays of parallel horizontal thin-wire antennas over the surface of an imperfectly conducting earth. The program is equipped to treat unequally spaced arrays of wires that can be of different lengths and radii, but it is assumed the wires are all centerfed. The wires are assumed to be unloaded and that the conductivity of the earth is finite. The effects of the imperfectly conducting earth are accounted for approximately by using the method of reflection coefficients. Computed output consists of current distributions, input impedances, and far-field patterns specified by the user.

Scientific Report No. 6

"Analysis of Radiation by Wire Antennas over Imperfect Ground," by T. K. Sarkar and B. J. Strait, Report AFCRL-TR-75-0337, May 1975.

ABSTRACT: Three user-oriented computer programs are presented and described for analyzing radiation from arrays of parallel vertical wires, parallel horizontal wires, and also arbitrary wire configurations over the surface of an imperfectly conducting earth. The first two programs are equipped to treat unequally spaced arrays of wires that can be of different lengths and radii and of arbitrary excitation and loading. The effects of the imperfectly conducting earth are accounted for in an essentially exact manner by using the Sommerfeld formulation. The third program treats arbitrary wire antennas and incorporates the ground effects approximately by using the reflection-coefficient method. Computed output consists of current distribution, input impedances, and field patterns specified by the user.

Scientific Report No. 7

"Radiation and Scattering from Large Polygonal Cylinders, Transverse Electric Fields," by J. R. Mautz and R. F. Harrington, Report AFCRL-TR-75-0343, June 1975.

ABSTRACT: This report deals with the computation of radiation and scattering of electromagnetic fields by electrically large convex conducting cylinders. A general computer program is developed for the case of transverse electric fields using the geometrical theory of diffraction. For a check of the computational accuracy, a computer program for a moment solution to the H-field integral equation is also developed. Illustrative computations are made for examples of radiation from a line source of magnetic current in the vicinity of a polygonal cylinder, scattering of plane waves, radiation from slots, and radiation from electric dipoles. Also given are examples of computations for conducting strips, grazing incidence on polygonal cylinders, and scattering from small cylinders. Complete program listings are included, with program descriptions, instructions for using, and sample input-output data.

Scientific Report No. 8

"A Generalized Network Formulation for Aperture Problems," by R. F. Harrington and J. R. Mautz, Report AFCRL-TR-75-0589, November 1975.

ABSTRACT: A general formulation for aperture problems is given in terms of the method of moments. It applies to any two regions isolated except for coupling through the aperture. The aperture characteristics are expressed in terms of two aperture admittance matrices, one for each region. The admittance matrix for one region is independent of the other region, and hence can be used for any problem involving that region and aperture. The solution can be represented by two generalized n-port networks connected in parallel with current sources. The current sources are related to the tangential magnetic field which exists over the aperture region when the aperture is closed by an electric conductor. Explicit formulations are given for two problems, that of an aperture in a conducting plane.

Scientific Report No. 9

"Analysis of Arbitrarily Oriented Thin Wire Antenna Arrays over Imperfect Ground Planes," by T. K. Sarkar and B. J. Strait, Report AFCRL-TR-75-0641, December 1975.

ABSTRACT: This work considers the analysis of antenna and arrays of thin wires of arbitrary orientation above imperfectly conducting ground planes. Emphasis is placed on the development of fast and accurate techniques for computation of the characteristics of antenna systems. An important problem is the evaluation of certain semi-infinite integrals encountered in the exact Sommerfeld solution. The time required for computation of these integrals is reduced by the application of interpolatory quadrature formulas. Where applicable, a modified method of steepest descent is used to evaluate the integrals. The approximate reflection coefficient method is derived from the Sommerfeld formulation via the method of steepest descent. The accuracy of the reflection coefficient method relative to the Sommerfeld method is discussed. Finally, formulas convenient for the optimization of various performance indices are discussed. Typical indices that have been optimized, both with and without constraints, are directivity, power gain, quality factor, and main beam radiation efficiency.

Scientific Report No. 10

"Electromagnetic Transmission Through a Rectangular Aperture in a Perfectly Conducting Plane," by J. R. Mautz and R. F. Harrington, Report AFCRL-TR-76-0056, February 1976.

ABSTRACT: A computer program is developed for calculating the transmission characteristics of a rectangular aperture in a perfectly conducting plane excited by an incident plane wave. The solution is obtained from the integral equation for the equivalent magnetic current using the method of moments. The expansion functions and testing functions are pulses in the direction transverse to current flow, and triangles in the direction of current flow. Quantities computed are the equivalent magnetic current and the transmission cross section patterns. To illustrate

the solution, computations are given for narrow slots and for square apertures. The computer program is described and listed with sample input-output data.

Scientific Report No. 11

"A Computer Program for Radiation from Arbitrarily Oriented Wire Antennas over Imperfect Ground," by T. K. Sarkar and B. J. Strait, Report RADC-TR-76-136, May 1976.

ABSTRACT: This report describes and lists a computer program for analyzing radiation from antenna arrays of arbitrarily oriented thin-wire antennas over the plane surface of an imperfectly conducting earth. The solution is that obtained from the E-field integral equation by the method of moments. The program input is the problem geometry, the array excitation and loading, and the characteristics of the earth. The program output is the current distributions on the wires, input impedances of the feed points, and the complex E-field at points in space specified by the user. Sample input-output data are included.

Scientific Report No. 12

"Transmission from a Rectangular Waveguide into Half Space Through a Rectangular Aperture," by J. R. Mautz and R. F. Harrington, Report RADC-TR-76-264, August 1976.

ABSTRACT: A computer program is developed for the problem of transmission of electromagnetic waves from a rectangular waveguide into half space through a rectangular aperture. The aperture may cover all or part of the waveguide cross section, but the sides of the aperture are parallel to those of the waveguide cross section. The solution uses the moment method applied to the integral equation for the equivalent magnetic current in the aperture. The expansion and testing functions are triangles in the direction of current, and pulses transverse to the direction of current. Quantities computed are the equivalent magnetic current, the reflection coefficient and equivalent aperture admittance seen by the incident mode, and the radiation gain pattern. The computer program is described and listed with sample input-output data.

IV. JOURNAL PUBLICATIONS

Journal publications relating to research performed under this contract are listed here.

1. "Pattern Synthesis for Loaded N-port Scatterers," R. F. Harrington and J. R. Mautz, IEEE Trans., vol. AP-22, No. 2, pp. 184-190, March 1974.

2. "Comments on Babinet's Principle for a Perfectly Conducting Screen with Aperture Covered by a Resistive Sheet," R. F. Harrington and J. R. Mautz, IEEE Trans., vol. AP-22, No. 6, p. 842, November 1974.

3. "Computational Methods for Antenna Pattern Synthesis," J. R. Mautz and R. F. Harrington, IEEE Trans., vol. AP-23, No. 4, pp. 507-512, July 1975.

4. "An Optimization Program for Linear Arrays of Parallel Wires," Computer Program Description, T. K. Sarkar, IEEE Trans., vol. AP-22, No. 4, July 1974.

5. "Generalized Network Parameters, Radiation, and Scattering by Conducting Bodies of Revolution," Computer Program Description, J. R. Mautz and R. F. Harrington, IEEE Trans., vol. AP-22, No. 4, July 1974.

6. "Radiation and Scattering from Loaded Bodies of Revolution," Computer Program Description, J. R. Mautz and R. F. Harrington, IEEE Trans., vol. AP-23, No. 4, p. 594, July 1975.

7. "Analysis of Radiation by Linear Arrays of Parallel Vertical Wire Antennas over Imperfect Ground," Computer Program Description, T. K. Sarkar, IEEE Trans., vol. AP-23, No. 5, p. 749, September 1975.

8. "Analysis of Radiation by Arrays of Arbitrarily Oriented Thin Wire Antennas Situated over an Imperfectly Conducting Earth," Computer Program Description, T. K. Sarkar, IEEE Trans., Antennas and Propagation, accepted for publication.

9. "Analysis of Radiation by Linear Arrays of Parallel Vertical Wire Antennas over Imperfect Ground," Computer Program Description, T. K. Sarkar, IEEE Trans., Antennas and Propagation, accepted for publication.

10. "A Generalized Network Formulation for Aperture Problems," R. F. Harrington and J. R. Mautz, IEEE Trans., Antennas and Propagation, accepted for publication.

11. "Characteristic Modes for Antennas and Scatterers," Chapter 3 in Numerical and Asymptotic Techniques in Electromagnetics, (Vol. 3 of "Topics in Applied Physics") Springer-Verlag, Berlin, 1975.

12. "An Impedance Sheet Approximation for Thin Dielectric Shells," by R. F. Harrington and J. R. Mautz, IEEE Trans., vol. AP-23, No. 4, July 1975, pp. 531-534.

13. "Radiation and Scattering from Large Polygonal Cylinders, Transverse Electric Fields," J. R. Mautz and R. F. Harrington, IEEE Trans., vol. AP-24, No. 4, July 1976.

14. "Radiation and Scattering from Conducting Cylinders, TM Case," D. T. Auckland and R. F. Harrington, IEEE Trans., vol. AP-24, No. 4, July 1976.

V. ORAL PAPERS

1. "Computer Solution of Field Problems," R. F. Harrington, given to the IEEE Joint Section on Antennas and Propagation, and Microwave Theory and Techniques, Huntsville, Alabama, September 17, 1973.

2. "Characteristic Modes and Their Uses for Antenna and Radar Problems," R. F. Harrington, given at the Naval Research Laboratory, Washington, D. C., January 8, 1974.

3. "General Purpose Computer Programs for Field Problems," R. F. Harrington, given to the IEEE Joint Section on Antennas and Propagation, and Microwave Theory and Techniques, Washington, D. C., January 8, 1974.

4. Same talk as (3), given to the IEEE Joint Section on Antennas and Propagation, and Microwave Theory and Techniques, Syracuse, New York, January 30, 1974.

5. "Recent Work on Computer Solution of Antenna and Scatterer Problems," R. F. Harrington, given to the IEEE Section on Antennas and Propagation, Columbus, Ohio, March 28, 1974.

6. Same talk as (2), given at George Washington University, Washington, D. C., April 4, 1974.

7. Keynote speaker at the IEEE Section Symposium, Boulder, Colorado, May 31, 1974.

8. "Optimization of Radar Cross Section of N-port Loaded Scatterers," R. F. Harrington and J. R. Mautz, URSI/USNC Spring Meeting, Atlanta, Georgia, June 12, 1974.

9. "Computational Methods for Antenna Pattern Synthesis," R. F. Harrington and J. R. Mautz, URSI Symposium on Electromagnetic Wave Theory, London, England, July 9, 1974.

10. "Numerical Methods for Solving Electromagnetic Field Problems," by R. F. Harrington, presented to Saint Louis Section IEEE, March 18, 1975.

11. "Computer Solution of Field Problems," by R. F. Harrington, presented to Philadelphia Section IEEE, April 15, 1975.

12. "A Surface Formulation for Characteristic Modes of Material Bodies," by Yu Chang and R. F. Harrington, IEEE International Symposium on Antennas and Propagation, University of Illinois, June 1975.

13. "Future Directions in Transient and Broadband Electromagnetics," R. F. Harrington, Discussion Panel, IEEE International Symposium on Antennas and Propagation, University of Illinois, June 1975.

14. "Coupling Through Apertures of Arbitrary Shape in Bodies of Revolution," by H. K. Schuman and B. J. Strait, IEEE International Symposium on Antennas and Propagation, University of Illinois, June 1975.

15. "Computational Methods for Transmission of Waves Through Apertures," R. F. Harrington and J. R. Mautz, National Conference on Electromagnetic Scattering, University of Illinois at Chicago Circle, June 16, 1976.

16. "Body of Revolution Modelling and Applications to EMC," H. K. Schuman and R. F. Harrington, International Symposium on Electromagnetic Compatability, Washington, D. C., July 15, 1976.

VI. PROJECT PERSONNEL

The following persons contributed to work under this contract:

Dr. Roger F. Harrington - Project Director

Dr. Bradley J. Strait - Co-director for the first two years

Dr. Joseph R. Mautz - Research Engineer

Mr. Tapan K. Sarkar - Graduate Assistant

Mr. Harvey K. Schuman - Graduate Assistant

Mr. D-C Kuo - Graduate Assistant

VII. RECOMMENDATIONS FOR FURTHER RESEARCH

Based on the results obtained on this project, the following topics are recommended for further research:

1. The solutions obtained for wire objects over an imperfectly conducting ground should be extended to conducting bodies of arbitrary shape over ground. Solutions to this problem could lead to the treatment of radar scattering from bodies over imperfect ground, radiation from antennas on vehicles over imperfect ground, and so on.

2. Further consideration should be given to radiation and scattering from large conducting bodies. The geometrical theory of diffraction is currently being studied by several groups of researchers, and this work should continue. Investigation of moment methods as applied to large bodies could lead to useful results, particularly if combined with the geometrical theory of diffraction and other asymptotic solution methods.

3. Many additional problems of engineering interest can be solved by the generalized network method given in Scientific Report No. 8. Examples of such problems are radiation from apertures in cavities, waveguide to cavity coupling, waveguide to waveguide coupling, and so on. These problems could be solved in detail in many cases, and general purpose computer programs written.

4. The generalized network treatment of aperture problems should be extended to include problems involving multiple regions and multiple apertures. Once this extension is formalized a number of specific problems could be treated. For example, arrays of cavity-backed antennas, cavities with multiple apertures, and scattering by multiple region bodies could be treated by such methods.

5. The generalized network formulation of aperture problems should be extended to the analogous treatment of multiple region problems without apertures. Such an extension would lead to the use of impedance or admittance matrices which apply to a single region only. Problems involving multiple regions could then be treated by properly combining the single region matrices. This solution would be useful for treating radiation and scattering problems involving several different regions, for example, conductors plus dielectrics.